Production of Electricity from Biomass Crops - US Perspective

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Abstract

In the United States, since 1973 there has been a dramatic increase in bioenergy use, especially in thermal and electrical applications of wood residues. For example the wood processing and pulp and paper sectors became about 70% energy self sufficient during this period. The amount of grid connected biomass fueled electrical capacity has increased from less than 200 MW_e in 1978 to over 7,500 MW_e today. This dramatic growth, stimulated in part by federal tax policy and state utility regulatory actions, occurred after the Public Utilities Regulatory Policies Act (PURPA) of 1978 guaranteed small electricity producers that utilities would purchase electricity at a price equal to the utilities' avoided cost. Nevertheless the electric power industry, and especially the biomass power industry, is facing uncertain times which are caused by utility deregulation initiatives, the expiration of PURPA contracts, and policy changes in the current Congress. At the same time, the agricultural sector may experience changes in commodity crop price supports in the 1995 Farm Bill, and is seeking reliable alternative and higher value markets for its products. The Farm sector is also under increasing pressure to dispose of residues in an environmentally acceptable manner, especially in-field straw and crop residue burning. In looking at the evolution of the biomass power industry, it is clear that two factors, increased power generation system efficiency, and the provision of reliable and cost-stable feedstocks are necessary for the stand-alone biomass power market to survive or grow.

Introduction

Today more than 70 percent of biomass power is cogenerated with process heat. Wood-fired systems account for 88 percent, landfill gas 8 percent, agricultural waste 3 percent, and anaerobic digesters 1 percent. There are nearly 1000 wood-fired plants in the U.S., typically ranging from 10 to 25 MW_e. Only a third of these plants offer electricity for sale. The rest are owned and operated by the paper and wood products industries for their own use. Most of today's biomass grid connected power installations are the smaller scale independent power and cogeneration systems. To date, utilities have been involved in only a handful of dedicated wood-fired plants in the 40 to 50 MW_e size range, and in some co-firing of wood and municipal solid waste in conventional coal-fired plants. Net plant heat rates for 25 MW_e plants in the California PG&E service territory average approximately 20 percent efficiency (17,000 Btu/kWh). By comparison the 43 MW_e utility-operated plant at Kettle Falls, Washington has a reported heat rate of 23.7% efficiency (14,382 Btu/kWh).

The advantageous power purchase agreements that were negotiated under PURPA in the 1980's are no longer available at high avoided cost rates. As a result a number of plants are closing as their power contracts come up for renewal. These plants could be competitive in today's environment using low cost waste and residue fuels if their efficiency was much higher. This has been demonstrated in the Hawaii sugar industry where the sugar mill power plants operate for a major part of the year as combined heat and power (CHP) installations. Investments in efficient steam cycles have resulted in a competitive rate of power generation under PURPA. Low pressure boilers were systematically replaced by higher pressure boiler systems of larger capacity in the period 1960 through 1980, with the average steam pressure and temperature increasing from 1.3 MPa and 210• C to 4.4 MPa and 380• C. Meanwhile the net steam consumption in the mills decreased significantly from 600 kg /tc (ton of cane) to about 300-400 kg/tc; resulting in a power output of about 60 kWh/tc on average, with the best mills reaching over 100 kWh/tc [Kinoshita, 1991][1].

Biomass power efficiency advances need to be competitive with low-cost fossil fuels, especially in stand-alone power generation. Such advances will require a considerable increase in the power-to-heat ratio and will require using advanced technologies, such as integrated gasification combined cycles (IGCC), as illustrated in Table 1.

Table 1. Comparison of present day steam generation with IGCC

Cost Factors (¢/kWh)	Steam Generation	IGCC
Operations and Maintenance	0.5	0.5
Fuel Only Cost	3.6	1.6
Capital Recovery	4.2	3.0-3.5
Cost of Electricity	8.3	5.1-5.6

Assuming a marginal cost of fuel of 2.0 $/GJ (approximately $38/tonne of dry biomass), a load factor of 85% (base loaded), and a return of 8% on capital invested per year, it is possible to see the effect of the new technology. Both plants are approximately 50 MW_e capacity. The efficiency of the steam plant is about 20%, while the IGCC is estimated to have an efficiency of 45%. The capital cost of the steam plant is $1800/kW, while that of the IGCC is expected to be in the range of $1300 to $1500/kW. As can be seen, the increase in efficiency has two effects: it reduces the capital cost on a kW basis, and it reduces the sensitivity of the final cost of electricity to the fuel cost component.

The California market established that an industry that is heavily reliant upon a fuel biomass that is predominantly composed of residues suffers from serious feedstock cost instability. It is clear that, once a market developed, the cost of fuel biomass (largely agricultural waste and residues) more than tripled over a ten year period. Further, the fuel cost continued to increase, albeit at a lower rate, until biomass power plants began to be bought out and shut down. As with any industry, a reliable feedstock supply available at a predictable price is necessary for the success of any biomass power facility. Thus there has been much interest in the use of dedicated feedstock supplies that should be

[1]C.M. Kinoshita. *Cogeneration in the Hawaiian Sugar Industry*. Bioresource Technology. 35(3). pp 231-237. 1991}

able to be contracted for to give some cost stability to the purchasing electrical generator.

Strengthening the link with Agriculture

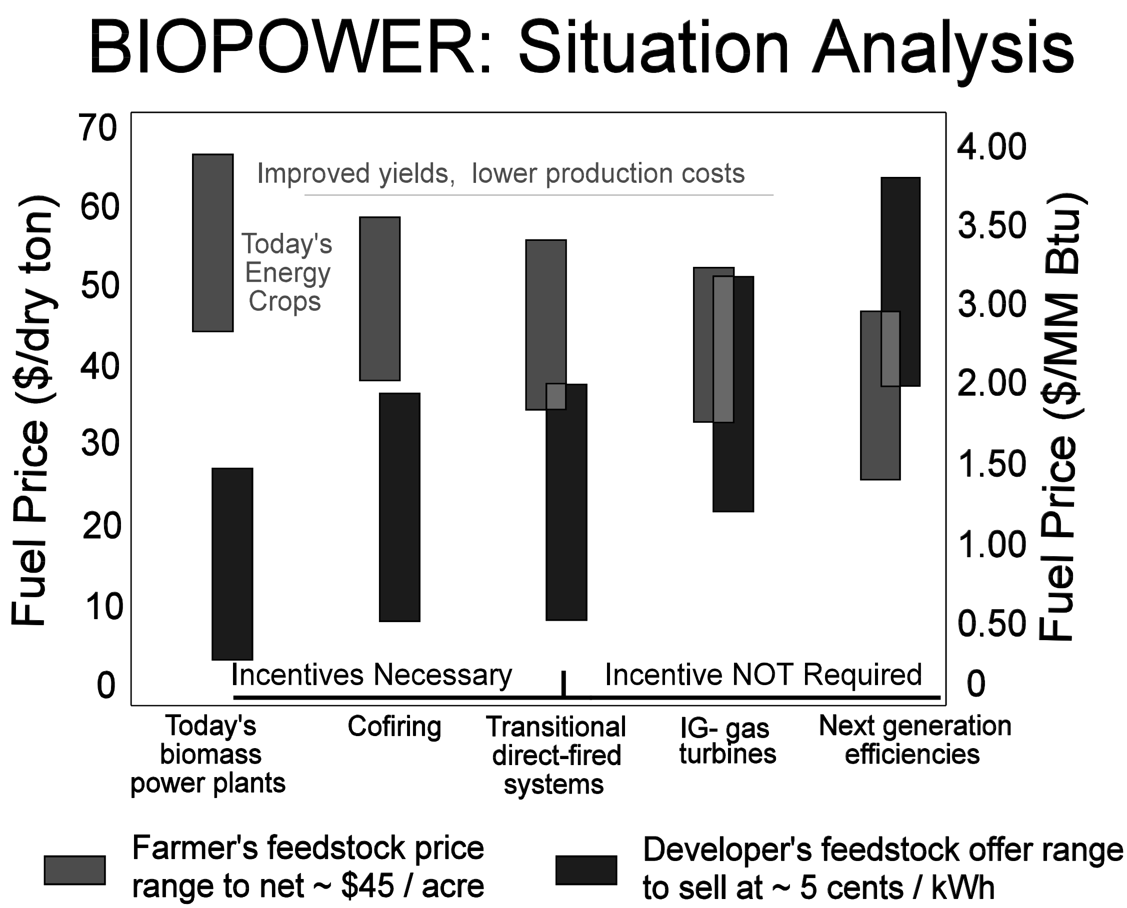
It became clear in the early 1990's that two factors, increased system efficiency and reliable and cost-stable feedstocks would be necessary for the stand-alone biomass power market to survive or grow. It was unclear, however, whether the technologies or feedstock supply systems would be available to meet this need. With this in mind, the DOE Biomass Power program in cooperation with EPRI, Oak Ridge National Laboratory (ORNL), and state energy agencies collaborated in solicitation and funding of the site-specific case studies listed in Table 2. These studies resulted in detailed assessments of the potential for biomass power systems and their associated fuel supply systems in economic, environmental, and social settings around the United States.

Table 2. "Economic Development Through Biomass Systems Integration" Feasibility Study Contracts Summary

Contractor	Location	Feedstock	Conversion Technology	Product(s)
PICHTR/ AMFAC	Hawaii	energy cane	gasification/ existing boiler	electricity sugar
Chariton Valley RC&D	Iowa	switchgrass, wood residues	gasification/ co-firing	electricity
Kansas Electric Utilities	Kansas	sorghum, switchgrass, block locust, silver maple, cottonwood	Fast pyrolysis/ combustion turbine	electricity biocrude charcoal
KENETECH Energy Systems	Puerto Rico	sugarcane, energy cane napier grass	direct combustion/steam cycle	electricity sugar
Niagara Mohawk Power Corp.	New York	willow	co-firing	electricity
Northern States Power	Minnesota	alfalfa	co-firing/ gasification combined cycle	electricity animal feed
Weyerhauser	North Carolina	pine	gasification combined cycle/ co-gen/ AMOCO ethanol process	electricity ethanol
University of Florida	Florida	elephant grass, sugarcane, eucalyptus leucaena	combustion/fermentation/ SSF ethanol process	ethanol electricity
PICHTR	Hawaii	sugar cane, bagasse, eucalyptus, alfalfa, corn sorghum	AMOCO SSF ethanol process/ gasification/ existing boiler	ethanol electricity animal feed sugar

Results from most of these studies have been received and will be published by DOE/NREL and EPRI. These studies generated a wealth of valuable data not only relating to the efficiency and cost of conversion systems but also to the viability, sustainability, cost, and environmental benefits of the supply systems. Interest in some areas (e.g. Minnesota) was so strong that biomass producers formed a cooperative with the intent of co-funding the power production facility.

The Gap.
An examination of the linkage of agricultural crops with power generation shows that the situation today is not economically viable. The crop producer costs are too high, and the price that the electrical generator can pay is too low. This is illustrated in figure 1.



The key for the crop producer is to raise the yields and reduce the crop maintenance costs. This is illustrated in the figure by the reducing curve of fuel price. For the electricity generator the challenge is to reduce the investment cost, and to increase the efficiency in order to obtain more kWh per tonne of feedstock. In the USA, one very near term opportunity is the use of biomass as a cofired fuel in large coal fired power stations. The capital cost of modifications to the predominantly pulverized coal fired units is in the range of 100 -300 $/kW whereas a new biomass fired plant would cost between 1500 - 2000 $/kW today. Even more advantageous is the observation that the co-fired biomass fuel enjoys the same efficiency of combustion and heat transfer that the coal does, something like 35% thermal efficiency in the average coal fired unit. Thus a transitional strategy that was proposed by the Niagara Mohawk study of willow as an energy crop is to use the crop in conjunction with wood wastes in cofiring with coal in order to build up the fuel supply infrastructure without major capital investment. Similar considerations apply to the Chariton Valley study of the use of a herbaceous energy crop in cofiring with coal in Iowa.

A Niche Strategy

The studies described in table 1., have demonstrated that the biomass systems' cost and performance can achieve levels that make them competitive or attractive in existing niche markets. Examples from the table and elsewhere indicate the nature of attractive niches that could propel the integrated biomass to electricity system to the marketplace.

The project in Minnesota has, like the United Kingdom a mandated non-fossil fuel mandate. Though no State in the US has adopted the UK - NFFO scheme, the legislature in Minnesota has set aside 125 MW (staged procurement of 50 MW before 1999, and 75 MW afterwards) for biomass power. The study by Northern States Power identified a co-product situation with CHP that creates a profitable project. The co-product is a flash dried, high value alfalfa leaf, the stalks fuel the power station which also supplies the energy for the leaf drying. Similar considerations with the coproduction of ethanol for gasoline blending in Hawaii, coupled with the sale of animal feed also creates a satisfactory return on a co-product, CHP project. Hawaii also creates a niche because there is no competing fossil fuel - all fossil fuels are imported to the islands and this integrated with rural development concerns as a consequence of the declining importance of the sugarcane industry creates a biomass power and liquid fuels opportunity. The Midwest of the USA and the Northeast are two regions that share concerns about rural development - and the lead organization on the Iowa switchgrass coal-cofire project is a body concerned with the economic development of the county that would supply the switchgrass fuel. Other areas will provide other niches, field disposal of straw residues by field burning is being legislated out of existence, the management of landfills requires that bulk materials should not be buried and this finds alternative use as a fuel in California for example.

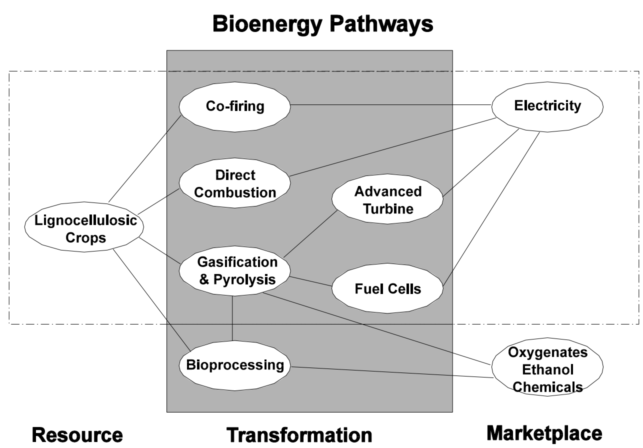
The number of these niches is in fact large both in the USA and in the EU. Their “summation” in effect reflects a large market opportunity for integrated biomass power - one that is already available to landowners and power project developers if there is a collective effort to leverage the activities in the different development sectors. It is clear that one way to facilitate entry to this market will be the development of “modular” fixed designs that when replicated, eliminate the front end engineering costs of plant design (since they are amortized over a series of similar or identical power plants) , and these will also facilitate the environmental assessment since by the same token they could have “type certification” much as aircraft have today, and is proposed for future nuclear electric developments. With increasing de-regulation of the national power grids the market will be very appropriate to the project developers that have put in place the non utility generating stations that now represent over half of all new capacity construction in the USA.

U.S. DOE BIOMASS POWER PROGRAM

The U.S. DOE Biomass Power Program is working with the private sector to address the issue of making biomass competitive by working with today's biomass power industry to increase its reliability and with equipment manufacturers and project developers to develop advanced systems for increased efficiency and environmental performance. Several factors contribute to the industry’s economic future - for the existing industry, improvements in efficiency are limited since these are set at the design stage, however, the availability of today’s industry results in typical load factors of only about 45%. The factors that affect the load factor are many, however in regions that have to use very diverse fuels which have high concentrations of alkali, there have been problems with boiler fouling.

Biomass fuel properties are limited by the inorganic composition.

It has been demonstrated operationally that biomass use in high efficiency thermal electricity generation is limited not by the properties of the organic component of Biomass, but by the behavior of the associated mineral matter at high temperatures. On a moisture and ash free basis, Biomass which has an average formula of $CH_{1.4}O_{0.6}N_{0.1}$ has a relatively low heating value of 18.6 GJ/t, however, this would not limit its use in high efficiency combustion systems since adequate high temperatures could be reached to achieve high carnot cycle efficiencies. These high temperatures cannot be reached because of the fouling and slagging propensities of the minerals in Biomass. The mineral composition is a function of soils and the growth habit of the Biomass, however the most important element is potassium, which either alone or in combination with silica can form the basis of fouling and slagging behaviors. Growing plants selectively concentrate potassium in their cells, which along with nitrogen and phosphorus are the key macro nutrients for plant growth. Annual plants tend to have very high potassium contents, while woody Biomass exclusive of the living cambial layer (i.e. minus the bark, small branches and leaves) has minimal contents of potassium and other nutrients. Under combustion conditions the potassium is mobilized at relatively low temperatures and can then foul heat transfer surfaces and corrode high performance metals used in the high temperature sections of burners and gas turbines for example. Recent work has demonstrated the phenomenology of ash fouling by the mainly potassium component of Biomass, as well as identifying the key species such as KOH, KCl, and sulfates that are involved in potassium transport at temperatures < 800 C. Techniques that separate the mineral matter from the fuel components (carbon and hydrogen) at low temperatures can avoid the alkali metal transport phenomena and result in very high efficiency combustion applications in combustors, gas turbines and diesel engines. Gasification and various types of clean up systems, as well as pyrolysis techniques are able to separate the minerals from the fuel component and provide the organic part of the biomass as a suitable fuel for high efficiency energy conversion in gas turbines, fuel cells and other engines. The conversion pathways being evaluated are shown in in Figure 2.



Support for today's industry

In general the biomass power industry has displayed good reliability, however, in the case of the independent power producer (IPP) biomass-fueled stations in California, operational difficulties rapidly emerged when using non-wood biomass fuels[2]. The operational difficulties were caused by the deposition of mineral matter on heat exchange surfaces (boiler tubes, superheaters, and water walls) and by the agglomeration of ash and inert fluid bed materials. This is a costly problem because results in down-time for tube cleaning and repair. Because there is

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[2] Jane Hughes Turnbull. 1993 *Use of Biomass in Electric Power Generation–The California Experience*, Biomass and Bioenergy Vol. 4. pp 75--84.

considerable interest in developing of dedicated crops such as short rotation woody crops and herbaceous energy crops for bioenergy applications, it could be a problem that would affect the long-term large-scale deployment of biomass fuels in both electricity generation and the production of liquid fuels. For this reason the U.S. DOE, through NREL, initiated a collaborative study with industry on the ash deposition problem[3] to establish the root cause of the difficulties in using non-traditional biomass fuels.

While the nature of the direct combustion boiler problem is of current concern, NREL also recognized that these same issues may have to be addressed in non-combustion processes such as fast pyrolysis and gasification that convert biomass into intermediate fuels used in very high efficiency generation systems based on gas turbines. Gas turbines are extremely sensitive to both mineral matter and alkali metals. For state-of-the-art turbines with turbine inlet temperatures of 1260• C (2300• F) the manufacturers specifications call for less than 300 ppb of alkali metal in the hot section. Because high efficiency biomass-to-electricity conversion is a goal of the U.S. DOE Biomass Power Program[4] a program of testing non-woody and short rotation biomass feedstocks in gasifiers and fast pyrolysis processes was instituted.

The ash deposition problem was addressed by conducting extensive fuels and deposits analysis, and through an extensive collaboration the cause was identified. The project received over 700 different fuels analyses from the participants, however, the majority of these did not have the critical ash analysis data. This may not have been such a bad omission because the project established that there are major problems with the standard ash determination methods that are accepted as standards for coal materials. The ASTM methods for coal prepare an ash at 800• C which is then used for the pyrometric cone analysis to determine if there will be slagging or stickiness problems. Unfortunately, the critical element causing the ash deposition and fouling problem is potassium, and it is known that this and other mineral matter from biomass will evaporate from the ash at 800• C, decreasing its mass and altering its fusion properties[5]. Potassium is a key component of cellular function, and in plants it can be present at 1000 times

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[3]Alkali deposits found in biomass power plants: a preliminary investigation of their extent and nature. NREL Subcontract TZ-2-1-11226-1. Principal Investigator: Thomas R. Miles of Thomas R. Miles Consulting Design Engineers. Participants: Delano Energy Company Inc.; Electric Power Research Institute; Elkraft Power Company (Denmark); Foster Wheeler Energy Corporation; Hydra Co Operations Inc.; Mendota Biomass Power, Inc.; National Wood Energy Association; Sithe Energies, Inc.; Thermo Electron Energy Systems; Wheelabrator Environmental Systems Inc.; Woodland Biomass Power Ltd.; Western Area Power Authority; Sandia National Laboratories; Hazen Research Inc.; Al Duzy and Associates; University of California Davis; U.S. Dept. of the Interior, Bureau of Mines; Appel Consultants, Inc.

[4]Electricity from Biomass. National Biomass Power Program Five-Year Plan (FY1994-FY1998). Solar Thermal and Biomass Power Division, Office of Solar Energy Conversion, U.S. Department of Energy, Washington, D.C. Draft, April 1994.

[5]M.K. Misra, K.W. Ragland, and A.J. Baker. 1993 *Wood Ash Composition as a Function of the Furnace Temperature*, Biomass and Bioenergy Vol. 4. pp 103-116.

the concentration of sodium. As much as 35% of the ash in annual plants can be alkali, which drastically reduces the ash fusion temperature from greater than 1300• C in the case of wood ash to about 700• C. At this temperature the potassium can form a eutectic with the plant's silica or the sand medium of the fluidized bed[6]. Work with the molecular beam mass spectrometer (MBMS) system at NREL has shown that the form in which potassium is transported can be very diverse including oxides, hydroxide, sulphite, sulfate, and chlorides as volatiles[7].

Gasification developments

Commercial biomass gasifiers already generate process heat and steam. Current development activities focus on producing electricity and, to some extent, liquid fuels, and involve integrating gasification with various cleanup systems to ensure a high-quality and reliable gas product. At this time, there is no clear preference for a single gasifier system. The Global Environment Facility[8], evaluated two systems offered by Scandinavian commercial developers for the CHESF project in northeast Brazil. The evaluation compared the advantages and disadvantages of using air gasification at high pressure (Bioflow) or at low pressure (the TPS system). High-pressure gasification would have to meet the pressure requirements of the chosen turbine on all system components, including the gas clean-up system; the low-pressure system would carry out the gas cleaning before compressing the fuel gas to the turbine operating pressure. Air blown systems produce only a low-heating value gas (less than 150 Btu/ft^3, 5-6 MJ/Nm^3), and a significant loss in efficiency is imposed if the gas must be cooled to ambient temperatures prior to being compressed. For this reason, the American and Scandinavian gasification programs are emphasizing using hot gas clean-up systems for the air-blown, low-heating-value gasifiers that will be operated at pressure. After a very extensive evaluation period, the project developers selected the low-pressure TPS gasifier for use in the proposed system.

The U.S. program has a dual-pathway strategy involving both low- and medium-heating-value gas production. One high-pressure system is capable of generating either low- or medium-heating-value gases according to whether it is an air- or oxygen-blown variant: the Renugas® system developed by IGT. The low-pressure strategy in the U.S. is based around development of medium-heating-value gas systems which do not use oxygen, but rather use indirect gasification

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[6]A. Ergundler, and A.E. Ghaly. 1993 *Agglomeration of Silica Sand in a Fluidized Bed Gasifier Operating on Wheat Straw*, Biomass and Bioenergy Vol. 4. pp 135-147. See also the phase diagram for SiO_2 - $K_2O.SiO_2$ in E.M. Levin, H.F. McMurdie, and F.P. Hall, 1956. *Phase Diagrams for Ceramists*. The Am. Ceramic Soc. Inc., Columbus, Ohio.

[7]D. Dayton, and T.A. Milne. Alkali, chlorine, SO_2, and NO_2 release during combustion of pyrolysis oils and chars. in Ed. T.A. Milne. Proceedings Biomass Pyrolysis Oil Properties and Combustion Meeting. September 26-28, 1994 Estes Park, Colorado. NREL-CP-430-7215. pp 296-308

[8]P. Elliott, and R. Booth. 1993. *Brazilian Biomass Power Demonstration Project*. Special Project Brief. Shell International: London, U.K.

to produce gases having heating values of 15 - 20 MJ/Nm^3. Cooling and quenching the gas does not incur a significant efficiency penalty, and compared with low-heating-value gas, there are essentially no modifications required in the turbine combustors to handle the medium-heating-value gas fuels.

The Pacific International Center for High Technology Research (PICHTR) Project (>6 MW_e)

The U.S. Department of Energy (DOE) and the state of Hawaii have joined with PICHTR in a cost-shared cooperative project to scale up the Institute of Gas Technology (IGT) Renugas® pressurized air/oxygen gasifier to a 45-90 ton/day engineering development unit (EDU) operating at 1-2 MPa using bagasse and wood as feed. The site is the HC&S sugar mill at Paia, Maui, Hawaii; NREL is providing project oversight in addition to systems analysis. The first phase, which is now being completed, consists of the design, construction, and preliminary operation of the gasifier to generate hot, unprocessed gas. The gasifier is designed to operate with either air or oxygen at pressures up to 2.2 MPa, at typical operating temperatures of 850• -900• C. In Phase 1, the gasifier has operated inside the envelope of a maximum feed rate of 45 ton/day at a maximum pressure of 1 MPa. In 1996 extended testing of the gasifier and a slipstream hot-gas cleanup unit is planned. The unit is sized such that a gas turbine could be added to the system to generate 3–5 MW_e of electricity.

The Vermont Gasifier Project with FERCO and the McNeil Generating Station (>15 MWe)

Future Energy Resources Company (FERCO) of Atlanta, Georgia, is the licensee of the Battelle indirect gasification system, and the scale up is at the site of the Burlington Electric Department's McNeil station in Burlington, Vermont. The project, which is in two phases, will first take feedstock from the 50 MW_e station, and after gasification will return the gas to the boiler. The scale of operation is about 200 tpd. The second phase will incorporate approximately 15 MW_e of turbine electricity generation. The project is jointly funded by U.S. DOE and FERCO, and ground breaking took place in the late Summer of 1995. Operations are planned to start in 1997 after a 16 month construction period[9].

National Renewable Energy Laboratory (NREL) Activities

The research strategy is guided by systems analysis and technoeconomic assessments of gasifier-based power cycles. In the laboratory, research is ongoing to develop catalysts for hot gas conditioning, and to use advanced instrumentation and chemometrics for feedstock characterization and evaluation. One element of this research is using advanced mass spectrometry to characterize alkali metal speciation under gasification and combustion of biomass conditions. This work has been extended to develop and use a transportable molecular beam mass spectrometer (TMBMS) for real time measurement of hot stream composition to 500

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[9] Moon, Susan. A Big Leap forward for Biomass Gasification. Biologue, Volume 13(3) pp 4 - 11, 1995

atomic mass units (amu). The TMBMS is being used by both Battelle and IGT to measure gasifier and catalyst performance in the field.

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